^{3}He Critical Point Measurements

M. Barmatz, Inseob Hahn and Fang Zhong
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109

and

Joseph Rudnick
Department of Physics
University of California at Los Angeles

Abstract

A theoretical analysis of the effect on the critical exponents of measurements along near-critical isochore and isotherm paths was performed. The uncertainty in the specific heat exponent, α and compressibility exponents, γ and δ along these near critical paths was determined. The construction of a specific heat cryostat was completed during the last year. At this time, we are in the middle of a long duration low-temperature run to evaluate the capability of this experimental system. Results of preliminary studies of the drift and pulse techniques for measuring the specific heat at constant volume are presented. The required temperature resolution for the microgravity experiment was demonstrated.

Introduction

The acronym MISTE (Microgravity Scaling Theory Experiment) has been given to the flight definition experiment to test the scaling hypothesis near the liquid-gas critical point of ^{3}He in a microgravity environment. This proposed experiment [1] will determine the critical exponents α, γ, and δ along the critical isochore and critical isotherm by performing a set of precision measurements of the specific heat at constant volume, C_V, and the isothermal compressibility, κ_T. A stringent test of the theoretical predictions for the measured critical exponents as well as the Renormalization Group scaling hypothesis between exponents will be performed.

Accuracy in Determining Critical Exponents

The accuracy in determining critical exponents strongly depends on the precise experimental path used to perform the measurements. We have analyzed the effect of a near critical isochore or isotherm path on the measurement of the critical exponents α, γ and δ in a zero gravity environment. The desired precision in the specific heat, C_V, and compressibility, κ_T, along a near critical isochore path is 1% down to a reduced temperature of $t = 10^{-7}$. A similar 1% precision is the goal for the compressibility along the critical isotherm to a reduced density of 5×10^{-4}. Calculations were performed using the Ginsburg-Landau-Wilson Hamiltonian for the liquid-gas universality class O(1). The critical exponents along critical paths used in the calculation are those obtained from High Temperature Expansions [2]. The predictions presented here were also shown to be consistent with calculations using the restricted cubic model [3].

Figure 1a shows the expected asymptotic deviation in the specific heat at constant volume, C_V, for measurements at varying reduced temperature, $t = T/T_C - 1$, along the near critical densities $\Delta\rho = \rho/\rho_C - 1 = 5 \times 10^{-4}$ and 1×10^{-3}. The deviation of C_V from critical isochore behavior is shown in Fig. 1b. One can obtain an effective critical exponent from a fit of the theoretically generated “data” to the expected critical asympotic power law expression. Using this fitting procedure on the “data” in Fig. 1a, the critical exponent α is predicted to shift by -0.31 and -1.2% for isochores that are 0.05 and 0.1% away from the critical isochore respectively.

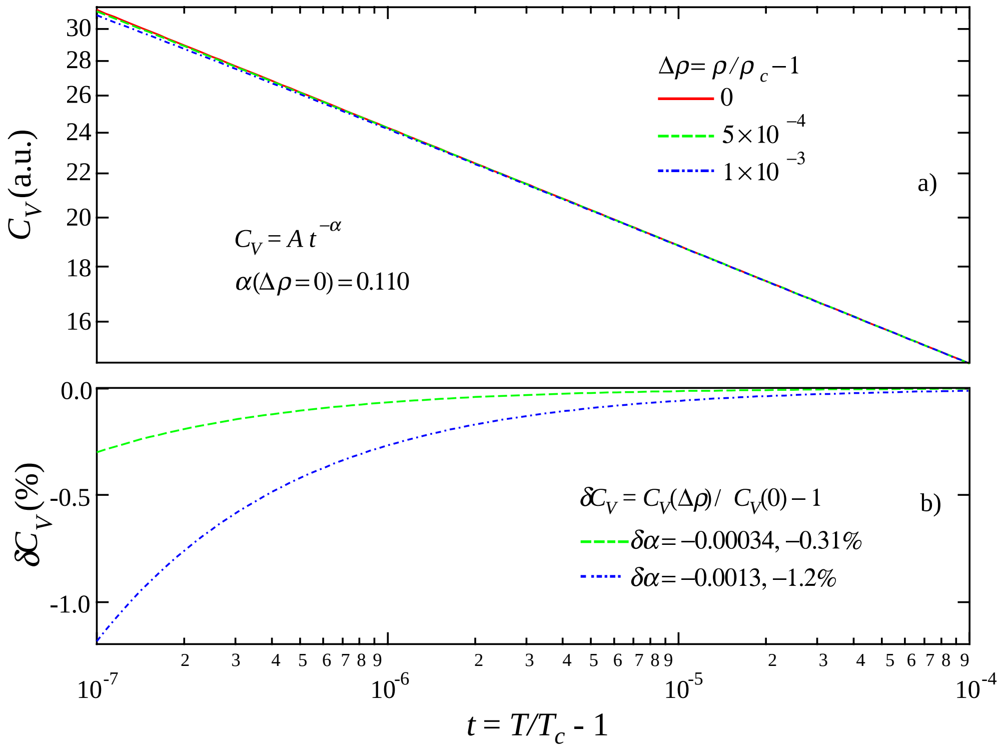

Fig. 1. Calculation of effective critical exponent α for C_V along near critical isochore paths.

Similar calculations for the isothermal compressibility, κ_T, along near critical isochores are shown in Fig. 2. The deviation of the critical exponent γ from critical isochore behavior for reduced densities of 0.03 and 0.05% is predicted to be -0.11 and -0.31% respectively. These results for C_V and κ_T show that in order to obtain an experimental accuracy of 1% in the critical exponents α and γ, deviations from the critical isochore must be less than 0.1%.

The calculations for the linear susceptibility, χ_T, which is related to the isothermal compressibility, κ_T, by the expression $\chi_T = \rho^2\kappa_T$, are shown along near critical isotherms in Fig. 3. For this case, because the critical exponent δ is so large, $\delta = 4.8$, significant errors in the exponent can occur even for very small deviations from the critical isotherm. The effective change in the critical exponent δ from critical isotherm behavior for reduced temperatures $t = 5 \times 10^{-9}$ and 5×10^{-8} is predicted to be 0.39 and 0.64% respectively. These results show that high resolution thermometry is required to obtain an experimental accuracy of 1% in the critical exponent δ.

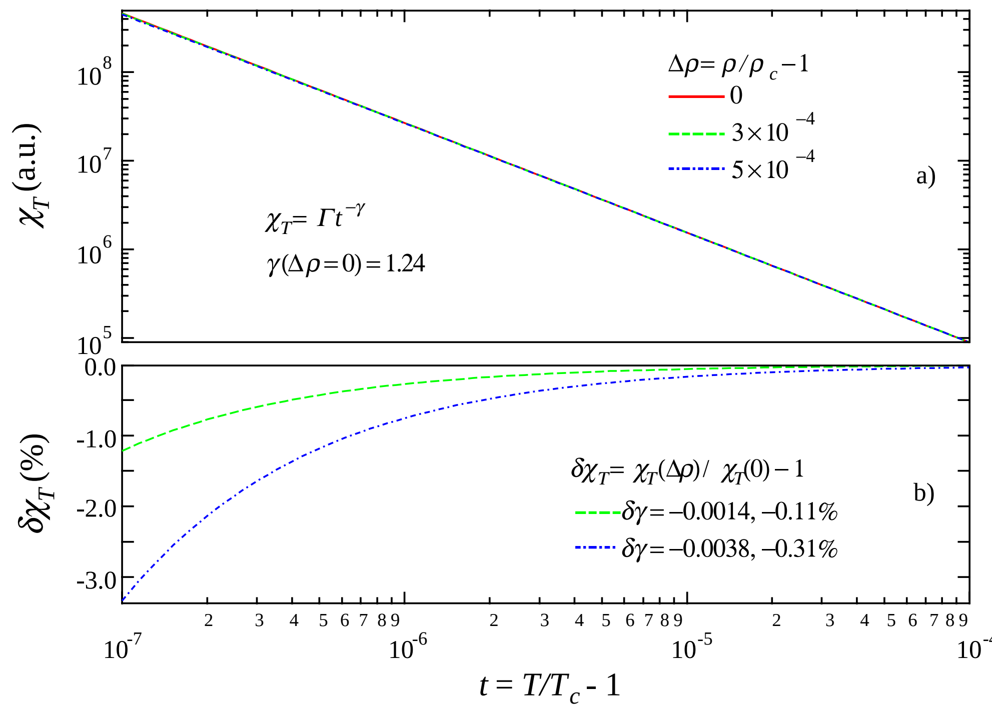

Fig. 2. Calculation of effective critical exponent γ for the linear susceptibility, χ_T, along near critical isochore paths.

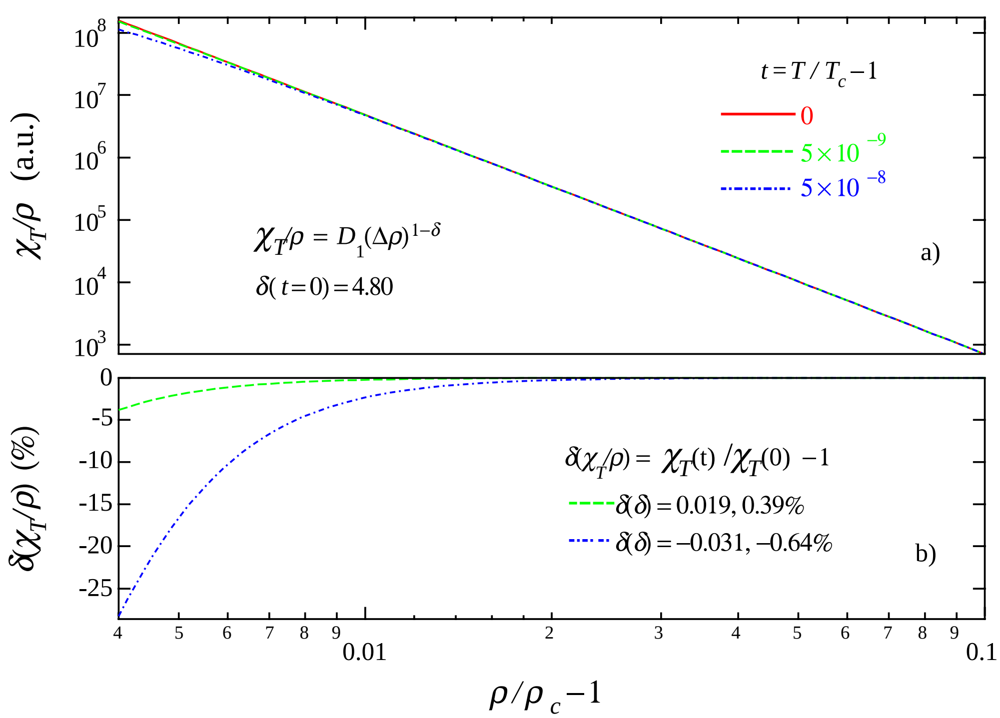

Fig. 3. Calculation of effective critical exponent δ for χ_T along near critical isotherm paths.

Fig. 4. Schematic showing heat transfer mechanisms between sample cell and shield stage.

The potential advantage of the drift method is the ability to perform C_V measurements upon cooling slowly through the critical point [4]. Figure 4 shows a schematic of the MISTE specific heat cell and surrounding shield stage. The main heat transfer mechanisms are conduction and radiation. The conduction path is primarily through the stainless steel supports between the cell and shield stage. Assuming a temperature difference $\Delta T = (T_0 - T_1)$ between the cell and shield, the conduction thermal resistance, R_C, is given by

$$R_C = \left(T_0 - T_1\right) / \left(dQ_C / dt\right) , \tag{1}$$

where Q_C is the heat conducted away from the cell. For small temperature differences ($\Delta T/T_C << 1$), one can similarly define a radiation thermal resistance R_r by

$$R_r = \left(T_0 - T_1\right) / \left(dQ_r / dt\right) , \tag{2}$$

with Q_r being the radiation energy leaving the cell. Using these thermal resistance definitions, the total heat capacity of the cell can be determined from the expression

$$C_T = -\left[\left(T_0 - T_1\right) / \left(dT_0 / dt\right)\right]\left[1 / R_C + 1 / R_r\right] . \tag{3}$$

It is assumed that the thermal resistances can be considered constant throughout the critical region. Thus, the precision in the measured total heat capacity is primarily dependent on the precision in measuring the cell and shield temperatures. At this time, the specific heat cell temperature is measured using a conventionally designed $GdCl_3$ high resolution thermometer (HRT) while a prototype miniature $GdCl_3$ HRT measures the shield temperature [5].

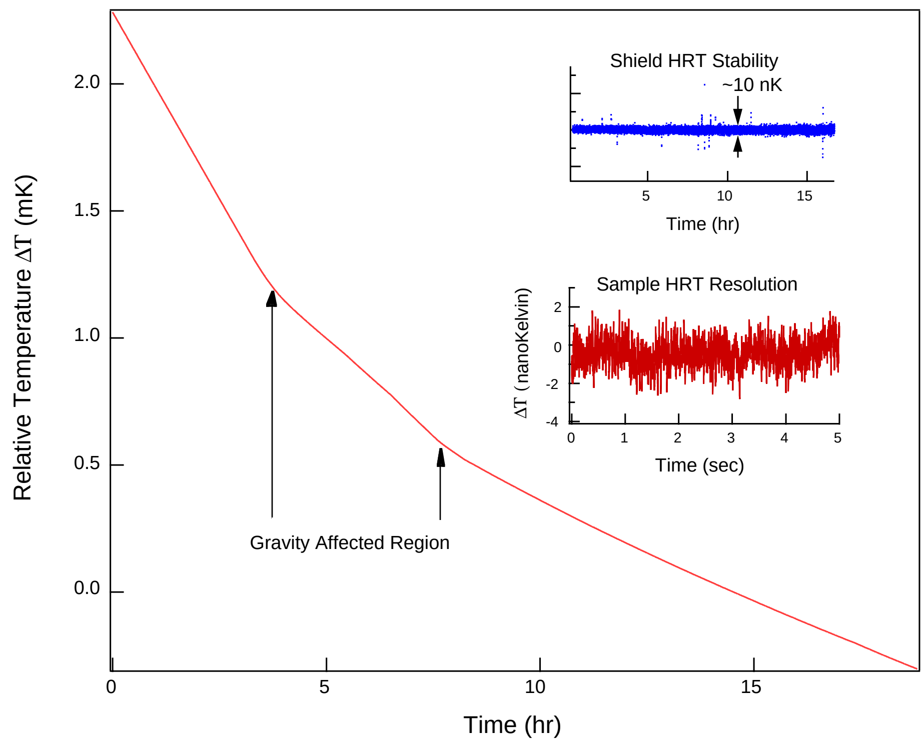

Fig. 5. Typical cooling drift experiment.

A typical cooling drift experiment slightly off the critical isochore is shown in Fig. 5. For this run, the shield temperature was held constant at ≈ 2 mK below the transition and the cooling rate was ≈ 150 μK/hr. The changes in slope, indicated by the arrows, define the gravity affected region ($t \approx 6 \times 10^{-4}$) near the phase transition. In a microgravity environment, this gravity induced smearing of the transition will be significantly reduced allowing more accurate measurements very near the transition. The inserts in the figure show the degree of stability and temperature resolution attained at the shield and cell stages. The shield temperature data shown here, which had no filtering, demonstrate that the shield stage could be held constant to much better than 10 nK for extended periods of time. The cell temperature data, with 100Hz filtering, show short term control to better that 1 nK. While further effort is required to develop the drift technique for measurements near the ^{3}He critical point, the inserts in Fig. 5 demonstrate that the temperature resolution required for the MISTE precision specific heat measurements has been attained.

Preliminary specific heat measurements have also been performed using the pulse technique. Figure 6 shows a sample heat pulse measurement at a reduced temperature of 3.5×10^{-4}. The sample cell was drifting upward in temperature at a rate of ≈ 3 nK/sec. The temperature rise was determined by fitting the temperature versus time data above and below the pulse to a straight line. The uncertainty in the temperature difference ΔT, between the drift rates above and below the pulse was ≈ 0.3%. This temperature resolution is sufficient for accurate pulse measurements to $t \approx 10^{-7}$.

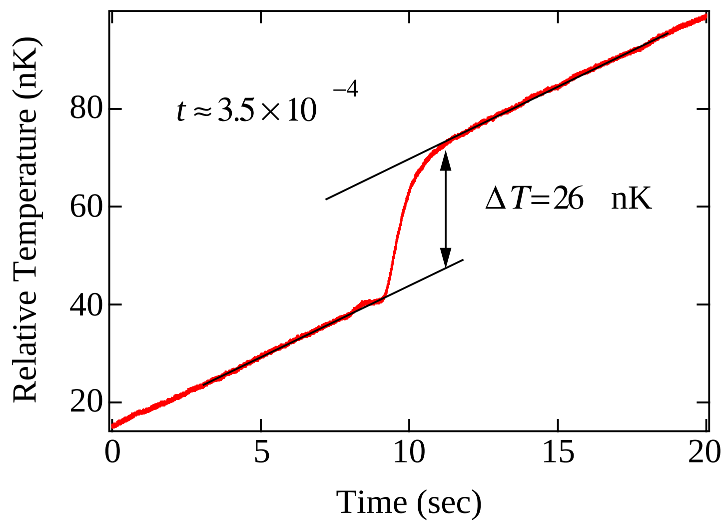

Fig. 6. Typical heat pulse measurement in the critical region.

Conclusions

We have performed the first extensive low temperature evaluation of the ground-based MISTE specific heat sample cell. Preliminary measurements of the drift and pulse specific heat techniques have demonstrated that the required temperature resolution for a microgravity experiment were obtained. The miniature $GdCl_3$ HRT provided the temperature resolution required for the shield stage. In the future, a similar miniature HRT will be tested on the sample cell. Replacing the conventional HRT design with a miniature unit will significantly reduce the volume and HRT calibration requirements of a future microgravity experiment. Future low temperature studies in the MISTE cell will evaluate electrostrictive techniques for measuring the isothermal compressibility in bulk [1] and finite size environments [6-9].

Theoretical estimates of the specific heat at constant volume and the linear susceptibility measured along near critical paths were also calculated. The maximum deviation from a critical isochore or critical isotherm path that will still permit 1% precision in the measured critical exponents α, γ and δ was determined by fitting the theoretically generated “data” to the expected critical asympotic power law expression.

Acknowledgments

We acknowledge the contributions of Dr. Chris Lindensmith to the preparation of this paper. The research described in this article was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

[1] M. Barmatz, Joseph Rudnick, Inseob Hahn, Ulf Isrealson and Bernard Zappoli, “Microgravity Test of Universality and Scaling Predictions Near the Liquid-Gas Critical Point of ^{3}He,” NASA Proposal, NRA-94-OLMSA-05 (1995).

[2] B.G. Nickel, Physica A, **106A**, 48 (1981); J. Zinn-Justin, J. Phys. (Paris) **42**, 783 (1981).

[3] J. V. Sengers and J. M. H. Levelt Sengers, *in Progress in Liquid Physics*, edited by C. A. Croxton (Wiley, New York, 1978), P. 103.

[4] J. Straub, A. Haupt, and K. Nitsche “Radiation Calorimeter for Heating and Cooling Ramps used for Hysteresis Measurements at Phase Transition,” Fluid Phase Equilibria, **88**, 123, (1993).

[5] M. Barmatz and Inseob Hahn, “Measurements Near the Liquid Gas Critical Point of ^{3}He,” *in the Proceedings of NASA/JPL 1996 Microgravity Low Temperature Physics Workshop, 1996, Pasadena CA*, NASA Report No. D-13845, p. 53.

[6] Joseph Rudnick and M. Barmatz, “Electric Fields near the Liquid-Vapor Critical Point,” *in the Proceedings of NASA/JPL 1996 Microgravity Low Temperature Physics Workshop, 1996, Pasadena CA*, NASA Report No. D-13845, p. 17.

[7] Joseph Rudnick and M. Barmatz, “Finite Size Effects near the Liquid-Vapor Critical Point,” paper in this Workshop Proceedings.

[8] Joseph Rudnick, M. Barmatz, and V. Dohm, “Finite Size Effects Near the Liquid-Gas Critical Point of ^{3}He,” NASA Proposal, NRA-94-OLMSA-05 (1995).

[9] Joseph Rudnick, M. Barmatz, and Fang Zhong, “Measurement of the Isothermal Compressibility in a Confined Geometry Near the Liquid-Gas Critical Point of ^{3}He,” NASA Proposal, NRA-96-HEDS-03 (1997).